The University of Reading

Met Office

Numerical Weather Prediction

Set-up and Testing UM 4.5 configurations for GOAP/Andhra-Pradesh

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Abstract

Delft Hydraulic and the Met Office are engaged in a joint project to supply systems for the forecasting of rainfall, wind and storm surge associated with cyclones that often affect Andhra Pradesh. This project forms part of the Andhra Pradesh Hazard Mitigation and Emergency Cyclone Relief Project, under the Government of Andhra Pradesh with the assistance of the World Bank.

A subsidiary part of this project is to supply the portable Unified Model (PUM) together with agreed configurations suitable for running over the area, and initial and boundary conditions for five test cases. This Report describes the domains supplied, and runs of the test cases on the Met Office T3E system. The test cases, which go back as far as 1990, use ECMWF analysis data as initial conditions. Meteorologically sensible results are produced, including the spin up of deep cyclones, though resolution precludes approaching the depth observed. It is concluded that, with data from the operational global model providing initial and boundary data, the models could provide useful forecasts. Recommendations are made regarding alternative domains.

Document History

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Set-up and Testing UM 4.5 configurations for GOAP/Andhra-Pradesh 3
Abstract 3
1 Introduction 7
2 NWP System characteristics 7
2.1 Initial model state 7
2.2 Lateral boundary conditions 7
2.3 Model resolution 7
2.4 Model formulation and Numerical approximations 7
2.5 Approximate parametrizations 8
3 Domains 8
3.1 Domain AP1 8
3.2 Domain AP2 9
3.3 Domain AP4 9
4 The Model 9
4.1 Configuration 9
5 Cases 10
5.1 Case 1: Orissa/Paradeep cyclone 25-29 October 1999 11
Observations 11
Choice of forecast start time 11
AP1 Results 11
AP4 Results 11
5.2 Case 2: Kakinada cyclone 4-7 November 1996 14
Observations 14
Choice of forecast start time 14
AP1 Results 14
AP4 Results 14
5.3 Case 3 : Bay of Bengal Severe cyclonic storm 29-31 October 1994 17
Observations 17
Choice of forecast start time 17
AP1 Results 17
AP4 Results 17
5.4 Case 4 Monsoon Floods 00Z 13th June 1996 20
Observations 20
Choice of forecast start time 20
AP1 Results 20
AP4 Results 20
5.5 Case 5 Monsoon flooding 00Z 26th September 1998 23
Observations 23
Choice of forecast start time 23
AP1 Results 23
AP4 Results 23
6 Comparison between Met Office runs and PUM results. 26
6.1 Case 1 27
6.2 Case 2 28

6.3 Case 3 **29**
6.4 Case 4 **30**
6.5 Case 5 **31**
6.6 Comments on comparisons **32**
7 Conclusions and recommendations ***32***

1 Introduction

Delft Hydraulic and the Met Office are engaged in a joint project to supply systems for the forecasting of rainfall, wind and storm surge associated with cyclones that often affect Andhra Pradesh. This project forms part of the Andhra Pradesh Hazard Mitigation and Emergency Cyclone Relief Project, under the Government of Andhra Pradesh with the assistance of the World Bank.

A subsidiary part of this project is to supply the portable Unified Model (PUM) together with agreed configurations suitable for running over the area, and initial and boundary conditions for five test cases. This Report describes the domains supplied, runs of the test cases on the Met Office T3E system and comparisons with equivalent runs on the PUM system in Andhra Pradesh.

The intention is to provide data to demonstrate the ability of the model to run in these circumstances, and as reference solutions for the model implementation in Andhra Pradesh. The results should not be taken as being in any way indicative of the accuracy that might be attainable using data obtained from the current operational UM.

2 NWP System characteristics

The UM is used as a forecast tool essentially by attempting to simulate the behaviour of the atmosphere by solving equations based upon the fundamental laws of physics. Hopefully, the simulation can be run faster than real events unfold, so that the weather that occurs in the model can be taken as an indicator of that which will occur in reality. It is well known that the governing equations exhibit chaotic behaviour, i.e. the results depend sensitively on the initial state and errors grow rapidly. Predictions depend on:

2.1 Initial model state

The smallest changes (e.g. 1 bit in the initial data) will eventually lead to divergence between forecasts; eventually such forecasts will just resemble random samples from the model climate. This is why assimilation of observations is essential to an NWP system. Furthermore, two analyses from different systems, while possibly equally consistent with data, will lead to different forecasts. Errors in forecasts are thus inevitable, and close attention must be paid to the source of data used in a forecast. A single run of a model cannot be used as literal truth, but rather interpreted in the light of experience of typical model errors at a particular forecast time (and in particular conditions). Note that initial state also includes variables such as sea surface temperature, important for cyclone dynamics.

2.2 Lateral boundary conditions

The forecasts discussed here are run in a Limited Area domain - thus, lateral boundary conditions are required throughout the model. These come from a global forecast model, sampled in time. Thus, information coming through the boundary has lower resolution in space and time, and higher resolution information must be generated internally by non-linear processes or surface forcing. These data are interpolated in space and time, which also introduces error.

2.3 Model resolution

Even if a model were perfectly accurate, it cannot represent features it cannot resolve. Most NWP models represent features of scale four or five times gridlength reasonably well, and attenuate smaller scale information. Thus, if one were to take an observed cyclone and average to the scales properly represented in an NWP model, one would expect to greatly smooth the results, filling in the centre of the cyclone to some extent and losing the intensity of the strongest winds.

2.4 Model formulation and Numerical approximations

No model is exact - some processes must be left out or simplified. This inevitably leads to systematic or random error. Even if the formulation is exact, the numerical solution leads to inevitable approximation.

2.5 Approximate parametrizations

Unresolved processes in the model have to be represented by model parametrizations (often termed 'physics', as opposed to adiabatic dynamics). A particular example is convection, which cannot be resolved and plays an important part in cyclone development. We do not know how to parametrize convection (or most other processes) exactly; thus, errors arise.

Thus, it is important to realise that no forecast will exactly agree with reality. Some errors are systematic (i.e. under-forecasting of central pressure or extreme wind due to model resolution), some quasi random (from initial state and model error). Furthermore, no forecast will exactly agree with another forecast unless made on exactly the same system with exactly the same data. This is a test which the UM routinely undergoes when code changes are made, but experience shows that exact agreement is a goal difficult to achieve on one system, and impossible to achieve between computer systems; the slightest difference between for example, mathematical libraries, will eventually lead to forecast divergence. We re-emphasise that no NWP forecast should be taken as literal truth - interpretation is required in the light of the climatology of model error.

3 Domains

Two domains were required. Resolution is specified in the Revised Action Plan G.O.Rt.No.38 20/1/2003. The initial domains were specified by K. J. Ramesh (03/12/2002).

3.1 Domain AP1

1. 0.18° Lat/Long grid. Since this is close to the equator, an un-rotated grid was regarded as more convenient; however, the UM, unmodified, has problems with un-rotated limited area configurations. Hence, a pole of 89.9999 °N, 180 °E was used. This leads to no significant error in positioning.
2. 5°S-35°N and 50°E-100°E.
3. 280 (W-E) x 224(N-S) grid points.
4. Land/sea mask taken from 10' US Navy data with inland sea points reset to land. 25605 land points.
5. Orography 10' US Navy data averaged to the appropriate grid. See Fig. 1 for a representation of the mask and orography.
6. Model setup. Using 5 minute timesteps (as UK mesoscale model, UKMES). Diffusion set to 5.0 x 10^6 del-4. This gives a 2 gridlength wave e-folding time of 0.72 dynamics timesteps, or 54s. This could probably be relaxed a bit (e.g. to 3.5 x 10^6, or 2.19 timesteps). Alternatively, a 7.5 minute timestep could be considered.

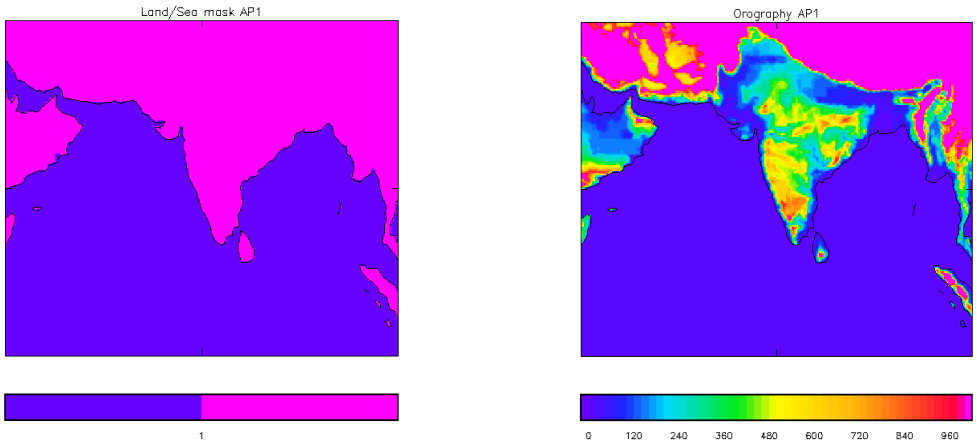


Figure 1. Land/sea mask and orography for domain AP1. Note that the colour scale is chosen to show the orography over most of India - the Himalayas etc. extend to extreme altitudes.

3.2 Domain AP2

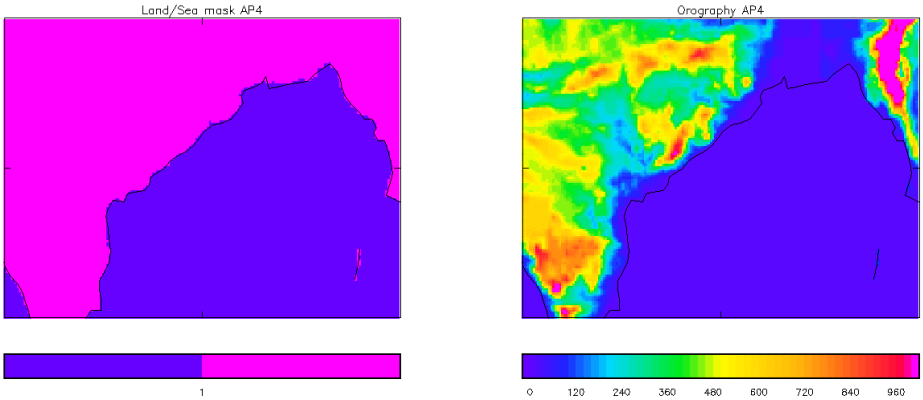


Figure 2 Land/sea mask and orography for domain AP4.

1. 0.11° Lat/Long
2. 5°S-35°N and 50°E-100°E.
3. 456(W-E) x 364 (N-S) grid points.
4. Land/sea mask taken from 10' US Navy data. 67900 land points.
5. Orography 10' US Navy data averaged to the appropriate grid.
6. Model setup. Using 5 minute timesteps (as UKMES). Diffusion set to 1.9 x 10^6 del-4 at UKMES.

Unfortunately, this domain proved impossibly large to run on the Met Office's T3E system; this has more grid-points than the global forecast model, and, in addition, has to store lateral boundary data. It was agreed to abandon this domain and implement a smaller area more similar to UKMES. (An alternative was considered but not pursued - hence the notation).

3.3 Domain AP4

1. 0.11° Lat/Long
2. 5°N-20°N/25°N and 75°E-90°E
3. 138 (W-E) x 182 (N-S) grid points.
4. Land/sea mask taken from 10' US Navy data with inland sea points reset to land. 13013 land points.
5. Orography 10' US Navy data averaged to the appropriate grid. See Fig. 2 for a representation of the mask and orography.
6. Model setup. Using 5 minute timesteps (as UKMES). Diffusion set to 1.9 x 10^6 del-4 (as UKMES).

4 The Model

4.1 Configuration

The model configuration used was based on that used operationally as the UK Mesoscale model when UM 4.5 was operational. The version operational up to 11 November 1999 was chosen; subsequent versions use the Edwards/Slingo scheme and MOSES II, which requires significant additional code to that in the PUM, and, in the case of MOSES II, data not easily available globally. Thus, the model uses Slingo and Wilderspin radiation, MOSES I hydrology and surface exchange, the 6A boundary layer (non-local) with orographic roughness, 3C convection with buoyancy closure, 3B mixed phase microphysics, and no gravity wave drag. Time stepping and diffusion are detailed above. Standard mesoscale (38) vertical levels were used. The models were run from analysis to T+48. It should be noted that, whilst the operational mods have been provided to the PUM installation team, the PUM code itself is not identical to UM4.5, so it is likely that differences will arise between the T3E runs and the PUM runs. These should be minor, but it should be remembered that the primary purpose is to provide initial and LBC data that has been demonstrated to run within the UM.

5 Cases

The cases chosen represent three cyclone cases and two Monsoon cases. The former were chosen with the hope of including the development and landfall of the cyclone within the 48 hour forecast, the latter chosen to represent the early stages. The cases required go back as far as 1994, the most recent being 1999. All the cases therefore lay outside the 18 month rolling archive that the Met Office retains of model analyses suitable for restarting the UM. The reason for the relatively short archive, in addition to cost, is that ECMWF is regarded as the primary source for model analyses.

For the 1999 case, the operational analysis from ECMWF used the 60 level version of their model, so this was used. For other cases, we elected to use ERA-40 re-analyses as these use the same 60 level model and essentially the same 3DVAR data assimilation system as the 1999 case, though, of course, different types of data were available historically. ERA-40 should be the best available analyses for such past cases, but it must be emphasised that analyses from the Met Office system would be in better balance with the UM, and would certainly have different, and, perhaps, better, representations of features such as tropical cyclones through bogussing (in addition to conventional DA).

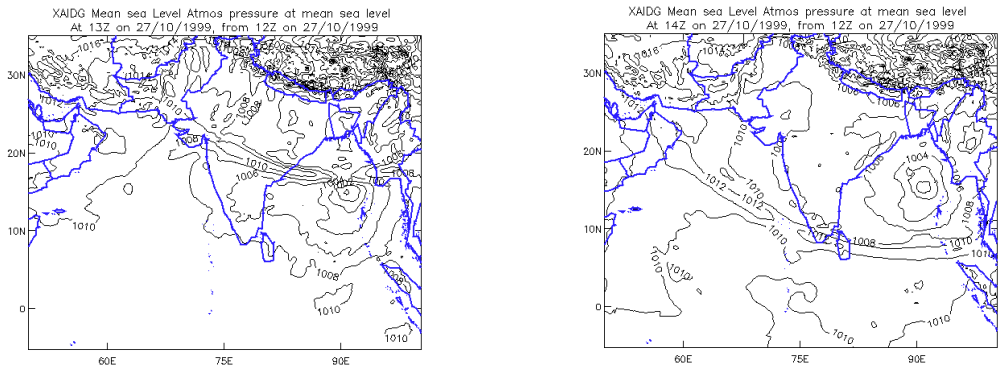


Figure 3. Example of initial transient from the Himalayas

In each case, model level data were retrieved from ECMWF at 1 degree horizontal resolution in GRIB format. UM 4.5 reconfiguration can make use of ECMWF GRIB but modifications were required to implement the 60 level set. The data were interpolated onto the UM global model (432x325 gridpoints, 30 vertical levels) and reconfigured to the UM global orography. The global model was then run to T+48, outputting lateral boundary conditions for all the above domains. The initial global analysis reconfigured to the global grid was then further reconfigured to each domain. It should be emphasised that no multiple nesting was used - the small, higher resolution domain, was also driven from the global model.

We repeat that the intention is to provide data to demonstrate the ability of the model to run in these circumstances, and as reference solutions for the model implementation in Andhra Pradesh. The results should not be taken as being in any way indicative of the accuracy that might be attainable using data obtained from the current operational UM.

Each of the model forecasts showed two distinctive features. The first is a pressure pulse emanating from the Himalayas from T+0. This leaves the domain in about 3 hours, so is not regarded as important. It arises, almost certainly, from the transformation from ECMWF levels to UM levels and would not be expected to affect runs initialised from the UM analysis. This is illustrated in Fig. 3. The effect, not surprisingly, is much smaller in AP4.

The second feature is a semi-diurnal oscillation in the surface pressure with amplitude typically 2 hPa. This may, at least in part, be a real (tidal) response to the strong diurnal heating cycle, but it may also come from a slight imbalance in the initial global data resulting in excitation of an external gravity wave. If this is the case, then the problem would not exist for initial and boundary data derived from the operational Met Office global model.

5.1 Case 1: Orissa/Paradeep cyclone 25-29 October 1999

Observations

1. Initial disturbance detected Gulf of Thailand 24th October 0000UTC in RSMC New Delhi synoptic charts.
2. Well marked low in morning of 25 on North Andaman Sea. By 25th October 1200 UTC centred 12.5N 98E in Andaman Sea.
3. Cyclonic storm 13.5N 95.0E by 26th October 0300 UTC.
4. Very severe cyclonic storm at 27th October 1500 UTC near 17.0 N 90.5E.
5. Eye clear 28th 0300UTC 17.5N 89.5E.
6. Pressure fell 56 hPa 28th October 0600 to 1800.
7. Lowest central pressure 912 hPa.
8. Winds Paradip 50 kt 29th October 0000 to 80+ kt 0200, Bhubaneswar 80+ kt 0700.

Choice of forecast start time

The observations suggested that a run from 1200 UTC 27th October 1999 to 1200 UTC 29th October 1999 would capture much of the development to landfall. Note that there is a warning on the ECMWF Website:

> "12 October 1999 Introduction of cy21r4 with 60 levels in the vertical for the reference model (T319)
>
> ECMWF has issued the following warning about this data.
>
> During the operation of cy21r4 of the ECMWF model from 12 October 1999 to 10 April 2000 the humidity fields in the lower stratosphere both in the analysis and forecast were seriously affected by erroneous moisture. These fields should not be used for research and it is recommended that the model results from the operational archive are not used to provide initial conditions for numerical experiments during this period.
>
> The error is up to 1 to 2 orders of magnitude in a shallow layer just above the tropopause. ".

It is unlikely, however, that this problem has a severe impact on the forecast.

AP1 Results

The initial data already contains a cyclone with central pressure about 999 hPa. This deepens steadily to 981 hPa at 12Z, 29th October (Fig. 4) compared with the estimated actual central pressure at 06 29th , just before crossing the coast, of 912 hPa. It is, of course, highly unreasonable to expect the model to achieve realistically low central pressures at this resolution. The cyclone track (Fig. 5) has been determined simply by locating the gridpoint in the area with the minimum sea level pressure. As such, it is a little erratic as the system deepens. The initial position is in error (consistent with the resolution of the ECMWF data) and the track actually moves towards the correct one. The general direction of motion is good. Landfall is too late, however. Fig. 6 shows the final pressure, precipitation and wind speed pattern. Precipitation rates above 32 mm/hr are achieved. Average 10 m windspeeds reach about 30 m/s (60 kt) around a distinct eye.

AP4 Results

Results are similar to AP1. The initial cyclone deepens steadily to 978 hPa at 12Z, 29th October (Fig. 7) compared with the estimated actual central pressure at 06 29th, just before crossing the coast, of 912 hPa. It is, of course, highly unreasonable to expect the model to achieve realistically low central pressures at this resolution. The cyclone track (Fig. 8) is a little erratic as the system deepens. The initial position is in error (consistent with the resolution of the ECMWF data). The general direction of motion is good. Landfall is too late, however. Fig. 6 shows the final pressure, precipitation and wind speed pattern. Precipitation rates above 32 mm/hr are achieved. Average 10 m windspeeds reach about 35 m/s (70 kt) around a distinct eye.

Overall, the track is arguably better, and the intensity marginally better, than the AP1 results.

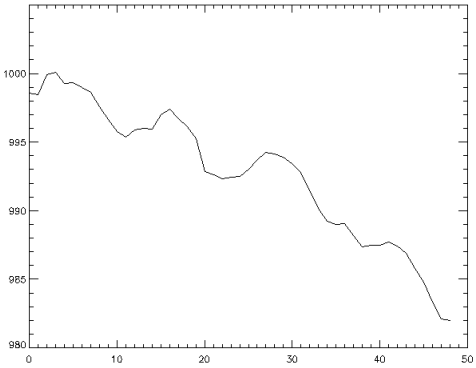


Figure 4. Case 1 AP1 modelled central pressure .

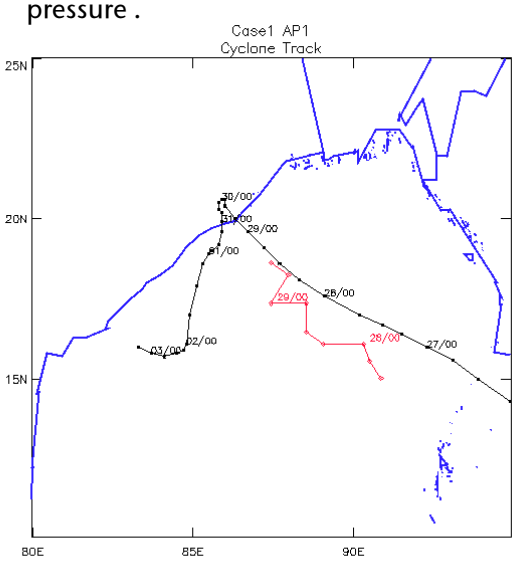
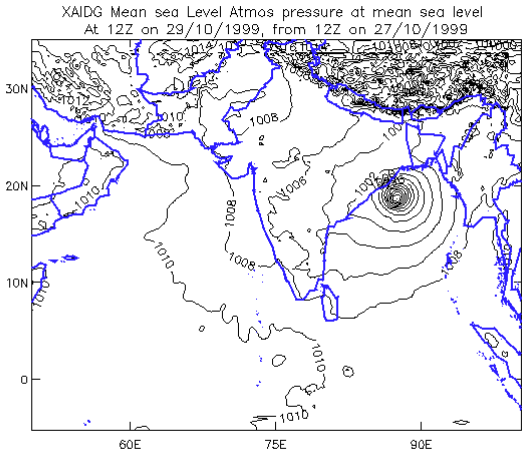
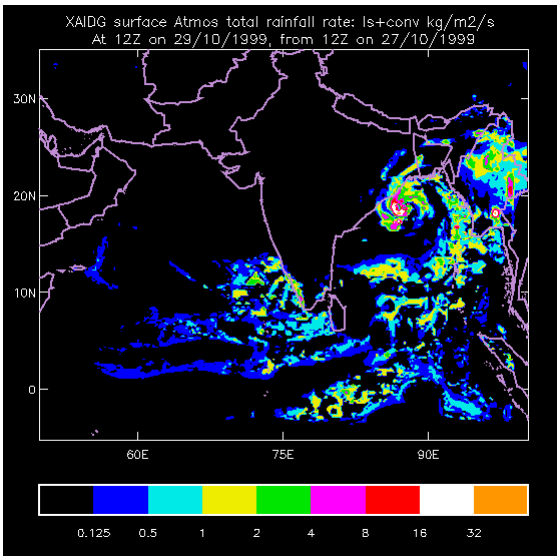


Figure 5. Case 1 AP1 Track (red) compared with actual





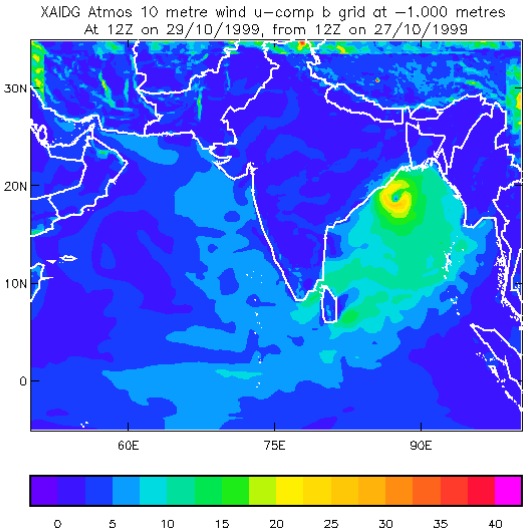


Figure 6. Case 1 AP1 PMSL, surface precipitation rate and 10 m wind speed at T+48.

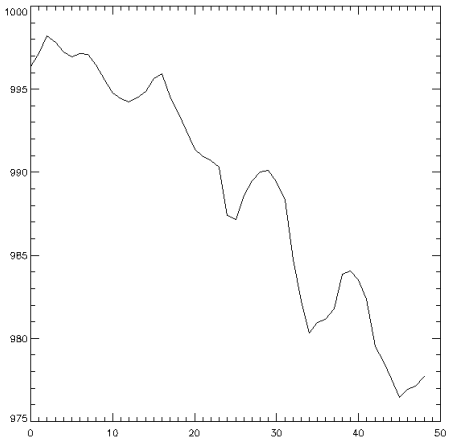


Figure 7. Case 1 AP4 modelled central pressure .

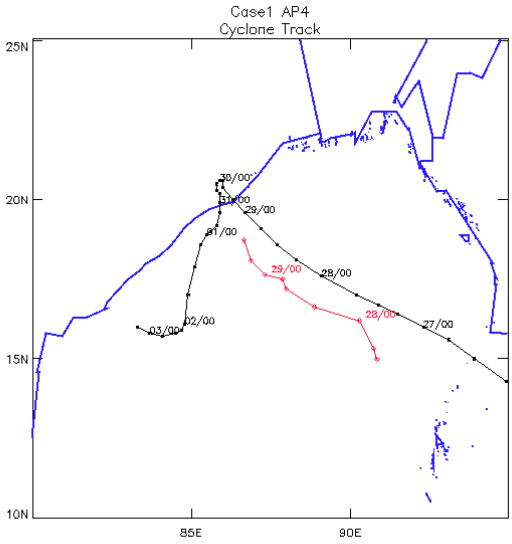
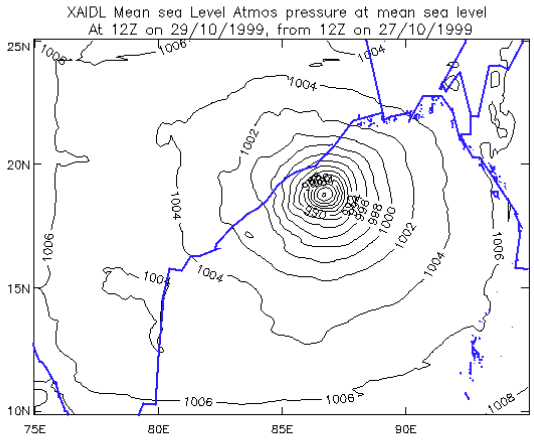
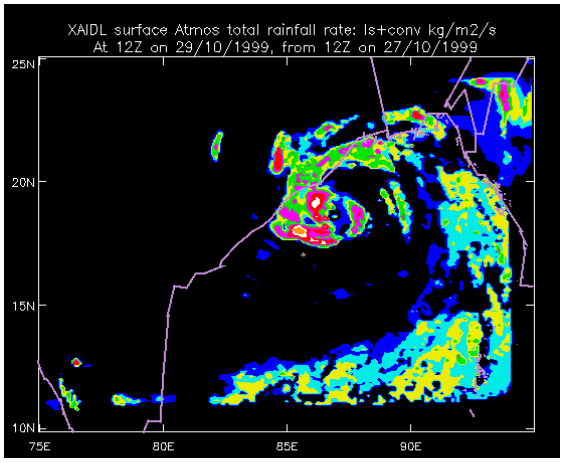


Figure 8. Case 1 AP4 Track (red) compared with actual





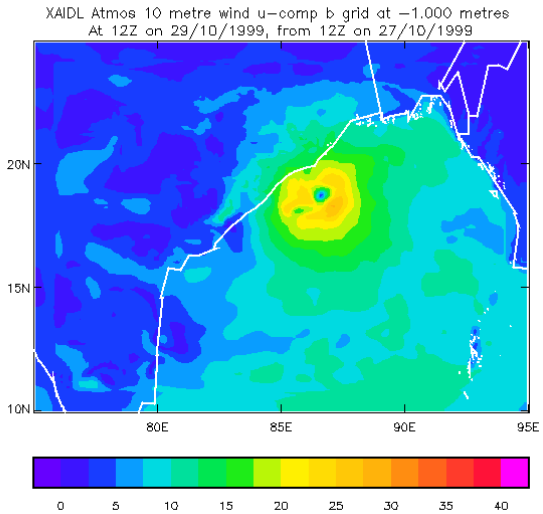


Figure 9. Case 1 AP4 PMSL, surface precipitation rate and 10 m wind speed at T+48.

5.2 Case 2: Kakinada cyclone 4-7 November 1996

Observations

1. Originated in well marked low over east central and adjoining west central Bay of Bengal evening of 4th November.
2. Intensified to depression by 1500 UTC 4th November centre near 16N 88E.
3. Cyclonic storm by 0900 UTC 5th November 16N 86E.
4. Landfall made 16UTC 6th November.

Choice of forecast start time

The observations suggested that a run from 00 UTC 5th November 1996 would capture much of the development to landfall.

AP1 Results

The run looks like a reasonable simulation (i.e. no major model problems) but is a poor forecast. A weak cyclone, associated with precipitation above 8 mm/hr, forms over the Bay of Bengal, but the cyclone fails to deepen and no extreme winds are produced. Average 10 m windspeeds barely reach about 10 m/s. The cyclone centre moves around (a result of its weakness), and the best that can be said is that it is located in the same region as the observed cyclone. A longer forecast may have spun up more, perhaps.

AP4 Results

The run looks very similar to AP1, with a little more intensity coming from improved resolution. Precipitation rates above 16 mm/hr. Average 10 m windspeeds reach about 15 m/s.

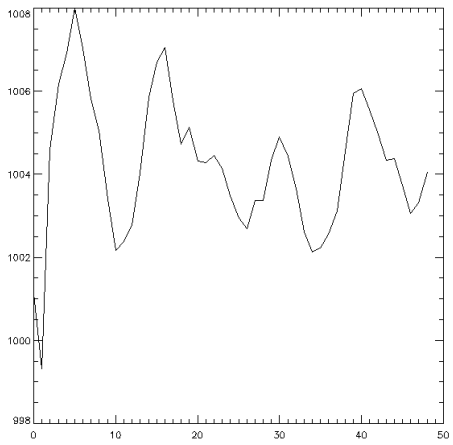


Figure 10. Case 2 AP1 modelled central pressure .

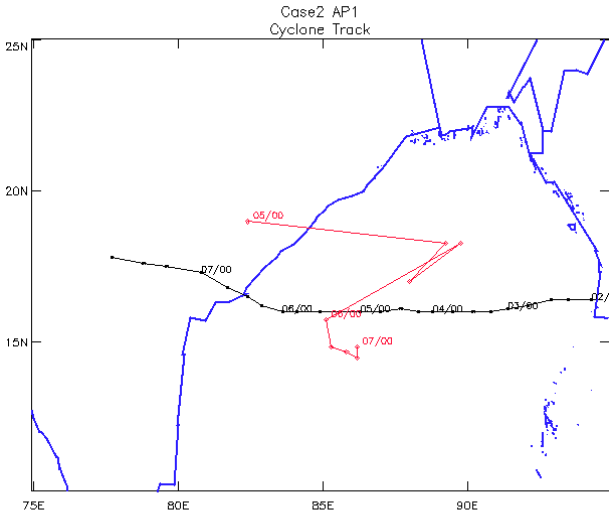
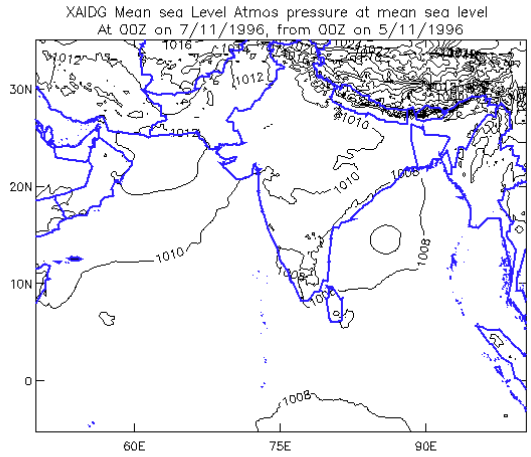
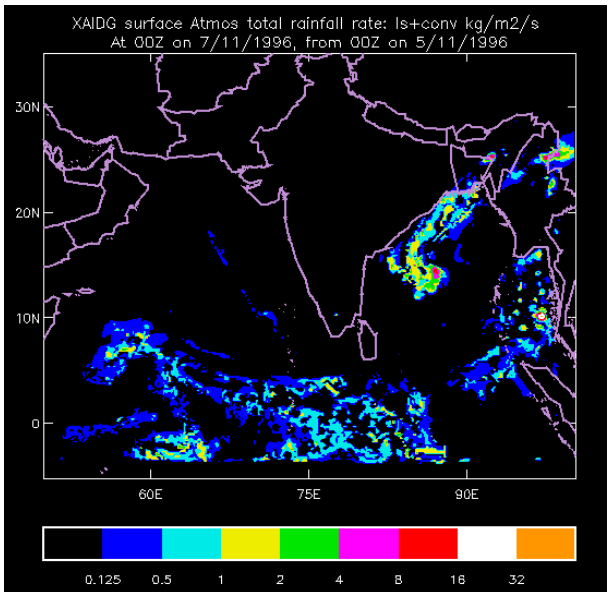


Figure 11. Case 2 AP1 Track (red) compared with actual





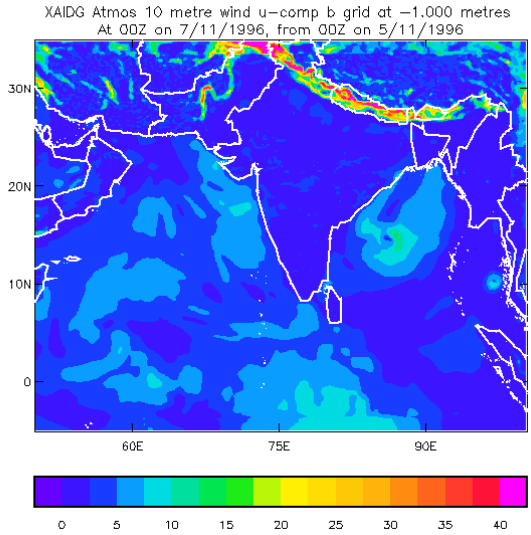


Figure 12. Case 2 AP1 PMSL, surface precipitation rate and 10 m wind speed at T+48.

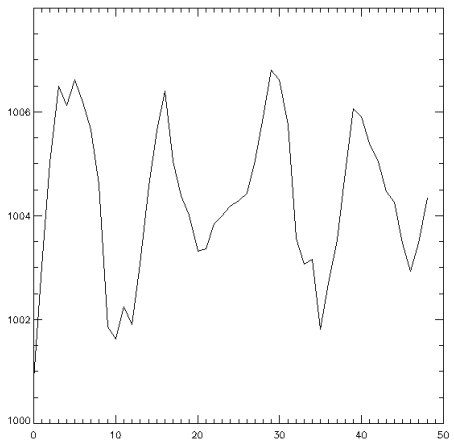


Figure 13. Case 2 AP4 modelled central pressure .

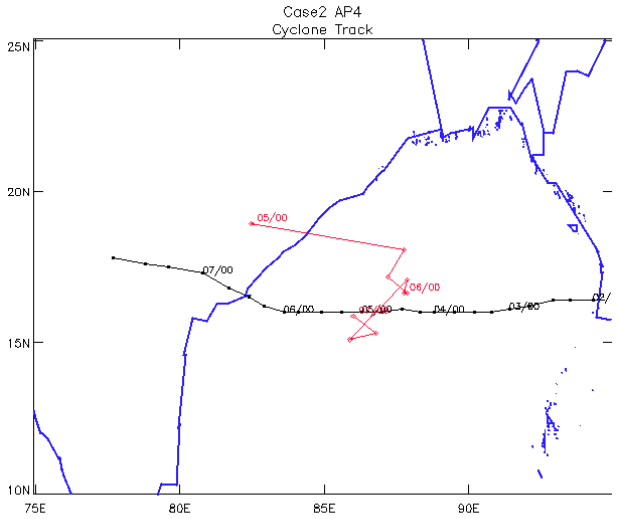
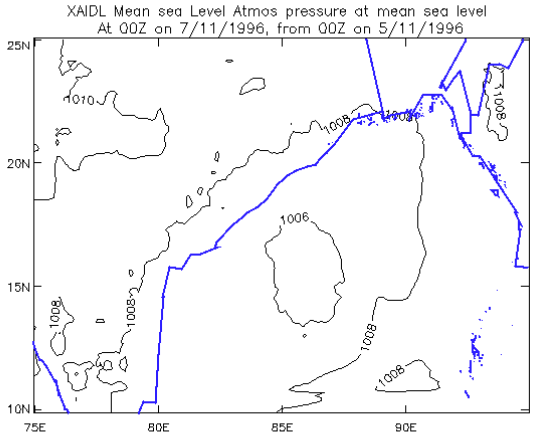
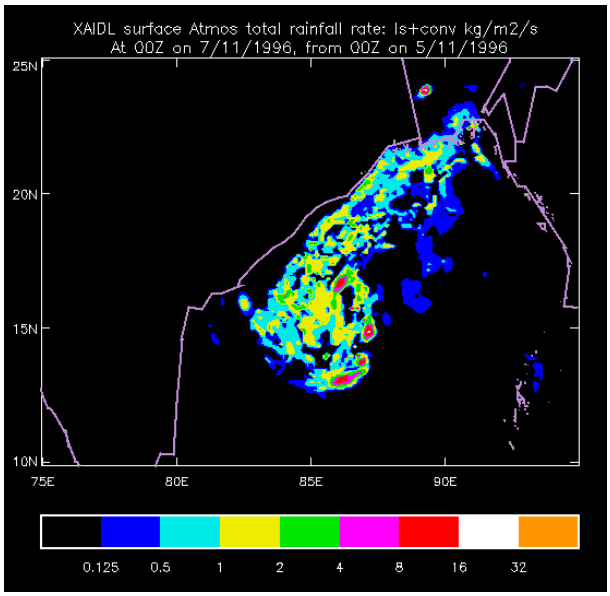


Figure 14. Case 2 AP4 Track (red) compared with actual





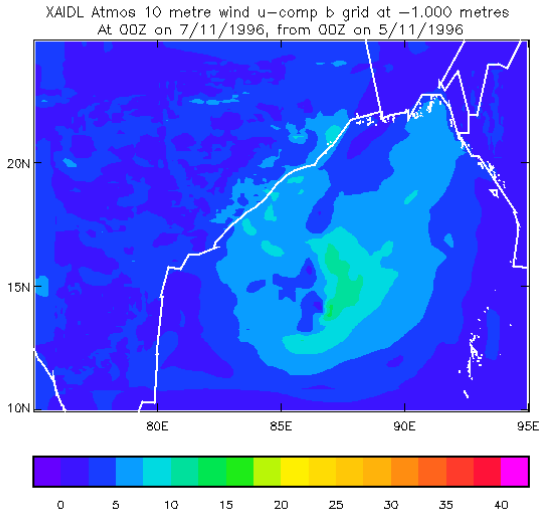


Figure 15. Case 2 AP4 PMSL, surface precipitation rate and 10 m wind speed at T+48.

5.3 Case 3 : Bay of Bengal Severe cyclonic storm 29-31 October 1994

Observations

1. Low formed over SW Bay of Bengal evening 28 October 1994.
2. Depression 9.5 N 85.0E 0300 UTC 29 October 1994.
3. Deep depression 10.5 N 84.5E 1200 UTC 29 October 1994.
4. Cyclonic storm 12.0 N 82.0 E 0300 UTC 30 October 1994.
5. Severe cyclonic storm 12.3 N 81.0 E 1200 UTC 30 October 1994.
6. Crossed coast 0100-0200 UTC 31 October 1994.
7. Centre 13.2 N 80.0 E 0300 UTC 31 October 1994.

Choice of forecast start time

The observations suggested that a run from 12Z 29th October 1994 would capture much of the development to landfall.

AP1 Results

The run looks like a reasonable simulation (i.e. no major model problems). There is no real depression in the initial data (even though there should have been). The model spins one up over about 12 hours, though the major deepening is after 24. Perhaps remarkably, once it does, the track is not too bad (Fig. 17). Landfall is reasonably close to the right place, though the timing poor. The weakness of the cyclone means average 10 m windspeeds barely reach about 15 m/s (Fig. 18).

AP4 Results

In this case, the cyclone track is very close to the edge of the AP4 domain. Though the model makes some attempt at forming something (with plenty of rain associated) the forecast is substantially worse than the AP1 domain (Figs 19-21).

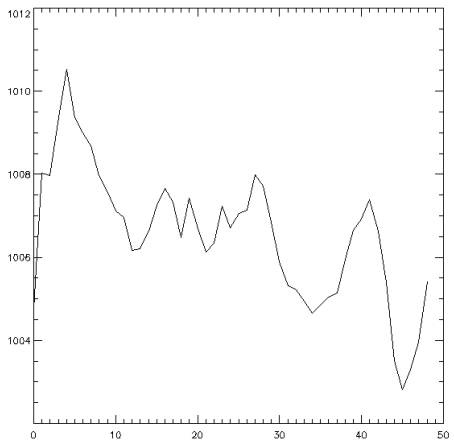


Figure 16. Case 3 AP1 modelled central pressure .

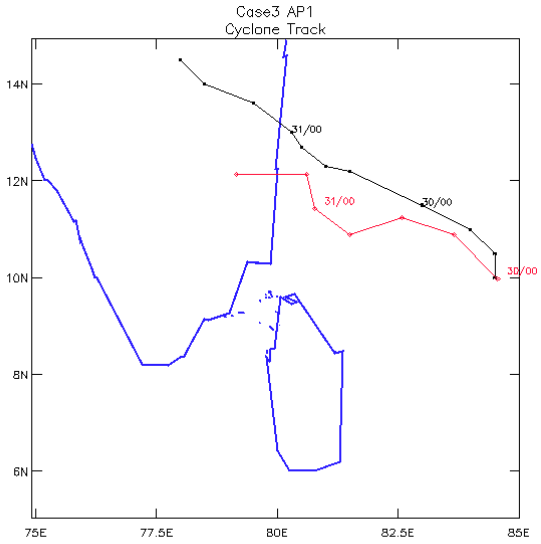
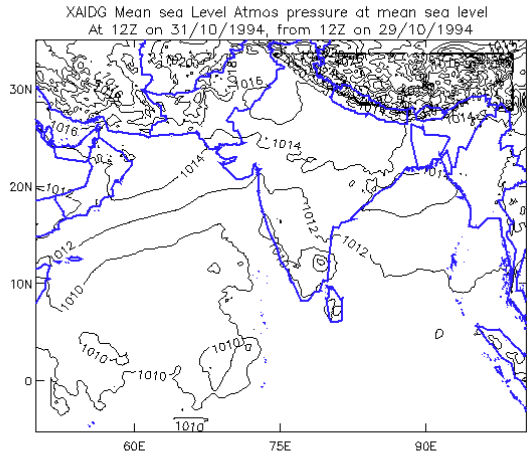
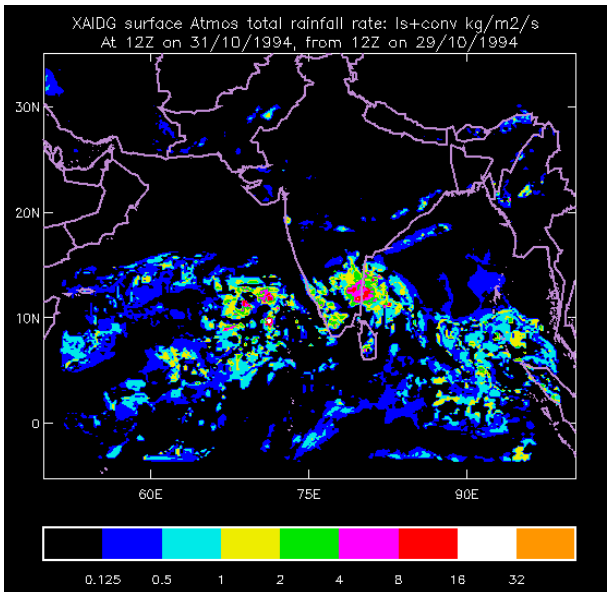


Figure 17. Case 3 AP1 Track from T+12 (red) compared with actual





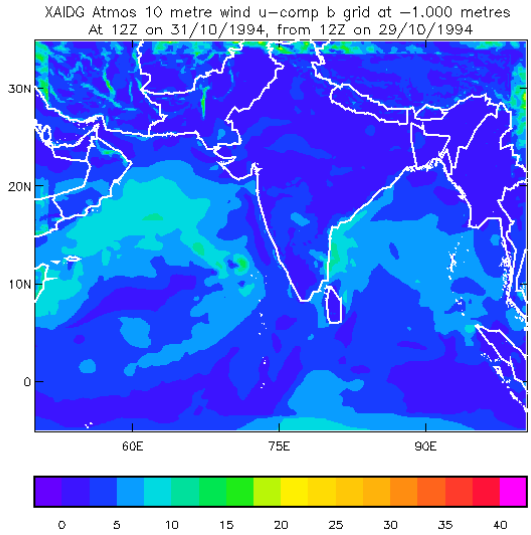


Figure 18. Case 3 AP1 PMSL, surface precipitation rate and 10 m wind speed at T+48.

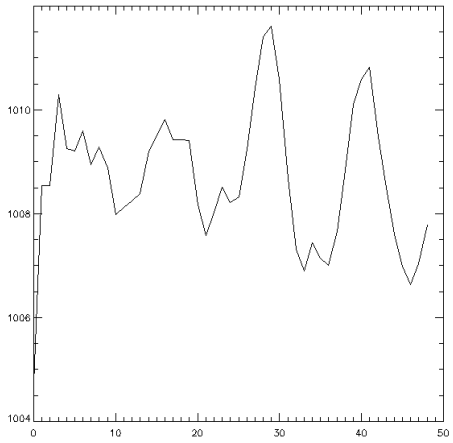


Figure 19. Case 3 AP4 modelled central pressure .

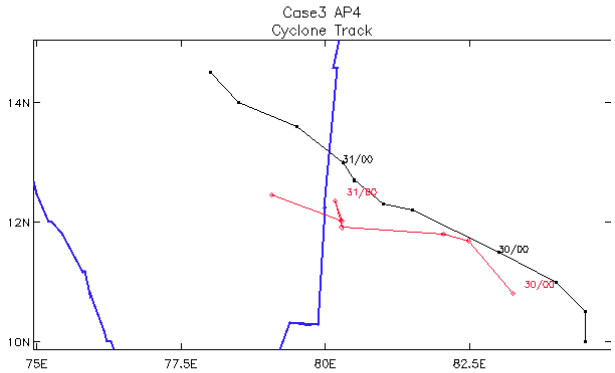
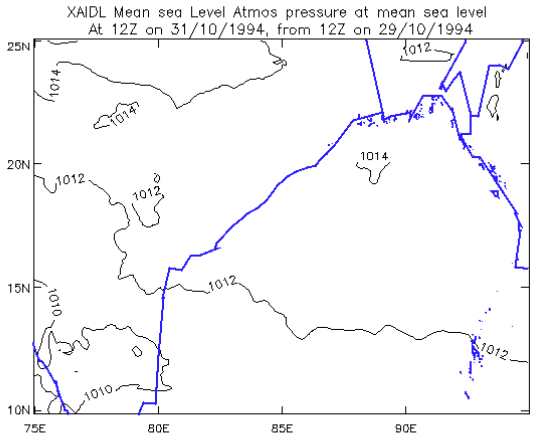
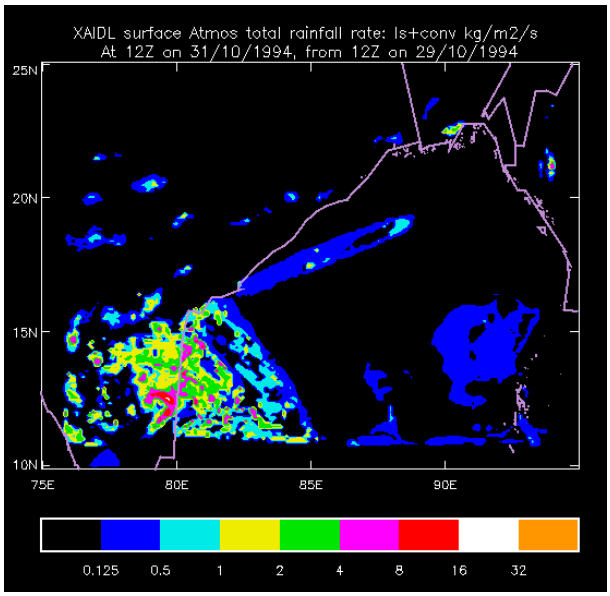


Figure. 20 Case 3 AP4 Track (red) compared with actual





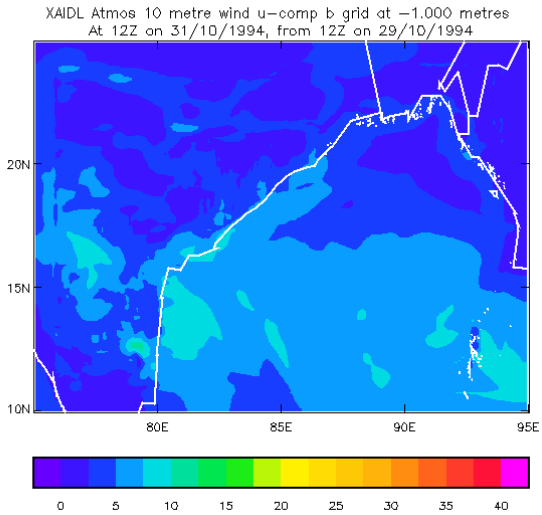


Figure 21. Case 3 AP4 PMSL, surface precipitation rate and 10 m wind speed at T+48.

5.4 Case 4 Monsoon Floods 00Z 13th June 1996

Observations

This case was chosen as a Monsoon flooding case. In fact, a cyclone did occur during the period. The cyclone track (Fig. 23) has been retrieved from the Met Office's statistical database.

Choice of forecast start time

The system was fairly slow moving. The observations suggested that a run from 00Z 13th June 1996 would capture much of the development close to landfall.

AP1 Results

The run looks like a reasonable simulation (i.e. no major model problems). There is a weak depression in the initial data. This steadily deepens to about 979 hPa (Fig. 22). The cyclone track is erratic (as it spins up), broadly in the right direction, but a little slow. Average 10 m windspeeds reach about 25 m/s. Given the initial state, perhaps a creditable attempt. In addition to the cyclone, there is a strong diurnal rainfall cycle in the convection scheme, and much rain falling over SW India. For information, the total rain over the 48 hour forecast is shown in Fig. 25. This shows accumulations exceeding 64 mm over the E coast and 256 mm over the SW coast of India.

AP4 Results

Again, these are comparable with AP1. The cyclone deepens somewhat more (~975 hPa). Average 10 m windspeeds reach about 30 m/s. The cyclone track is erratic (as it spins up), broadly in the right direction, but a little slow. It would appear that the cyclone rain does not penetrate as far inland over the period as the AP1 simulation. The impact of the 8 point boundary zone on the precipitation field is clear.

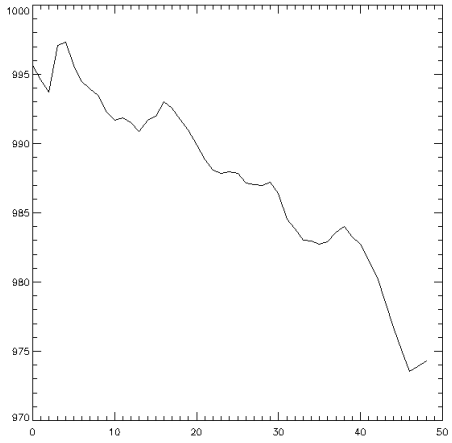


Figure 22. Case 4 AP1 modelled central pressure .

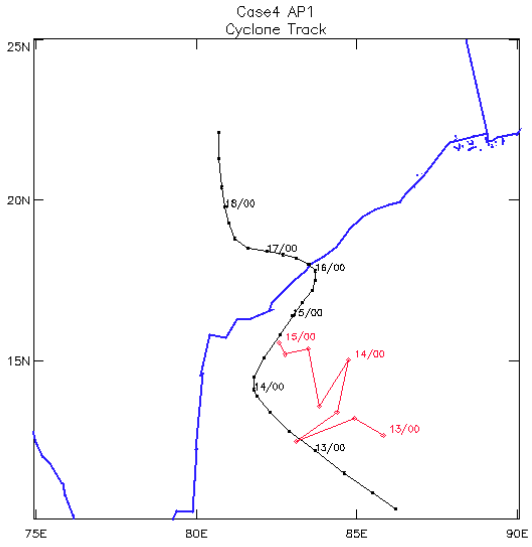


Figure. 23 Case 4 AP1 Track (red) compared with actual

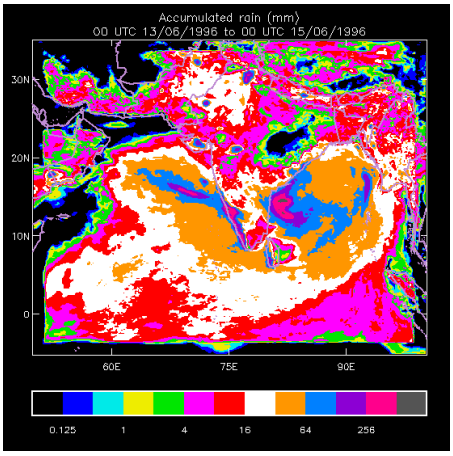
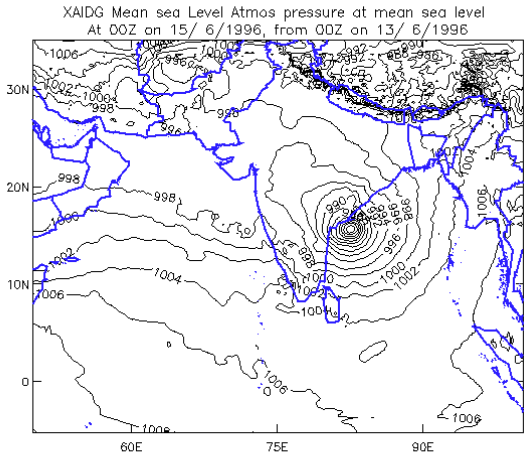
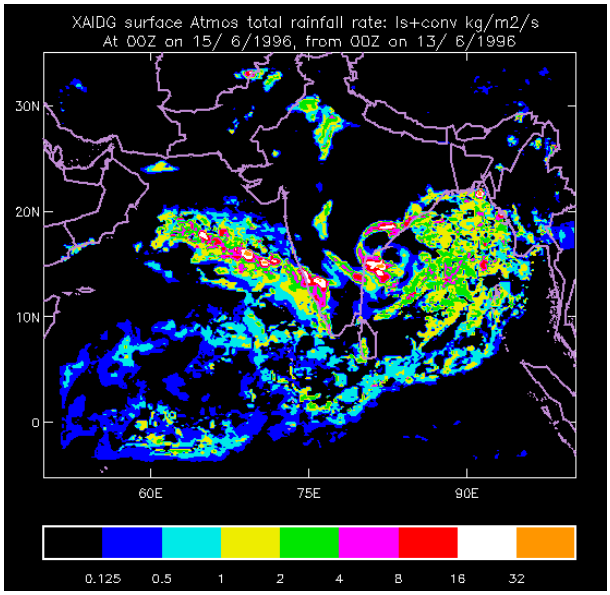


Figure 25 Total rainfall over 48h





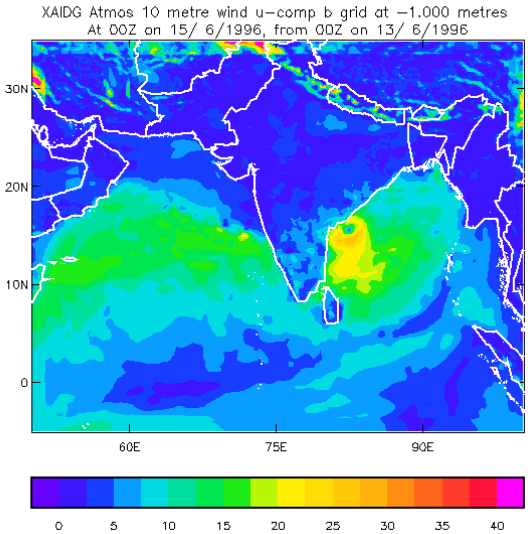


Figure 24. Case 4 AP1 PMSL, surface precipitation rate and 10 m wind speed at T+48.

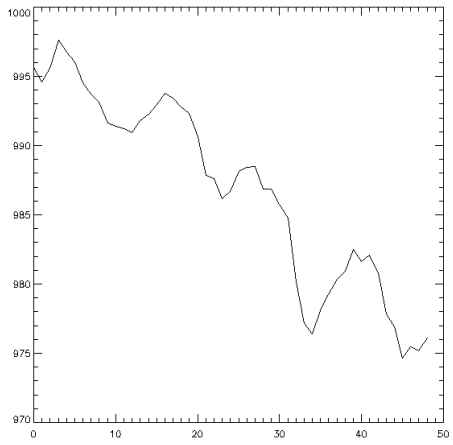


Figure 26. Case 4 AP4 modelled central pressure .

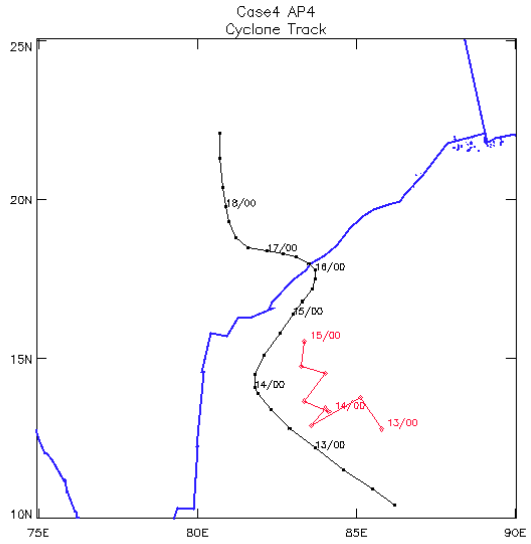


Figure. 27 Case 4 AP4 Track (red) compared with actual

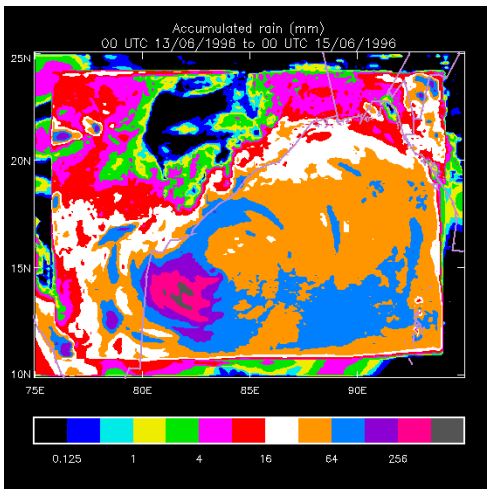
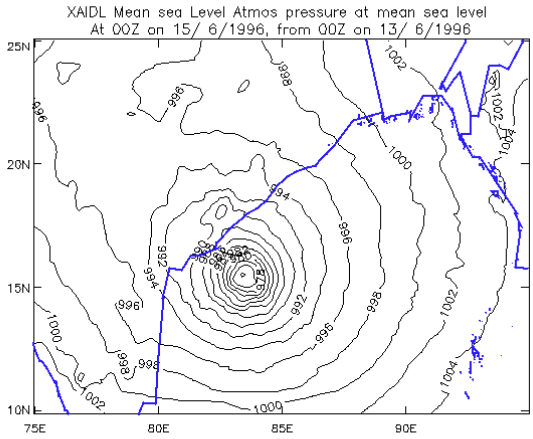
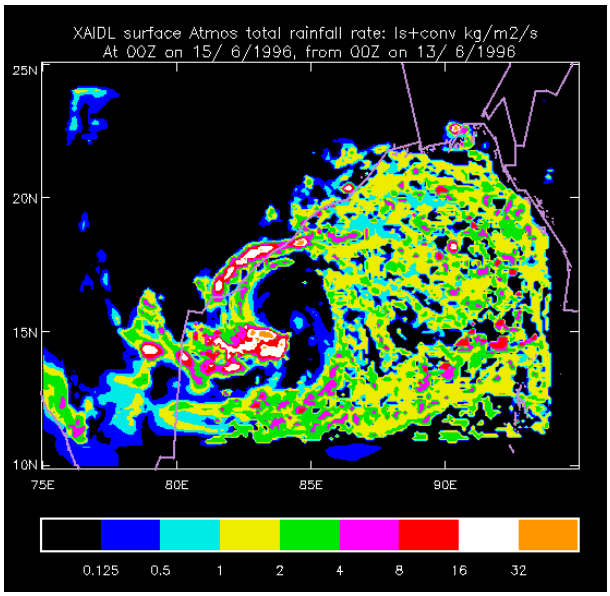


Figure 29 Total rainfall over 48h





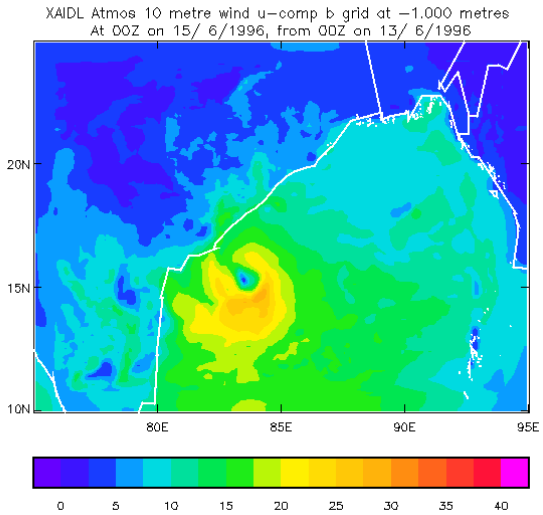


Figure 28. Case 4 AP4 PMSL, surface precipitation rate and 10 m wind speed at T+48.

5.5 Case 5 Monsoon flooding 00Z 26th September 1998

Observations

This case was chosen as a Monsoon flooding case. No cyclone occurred during the period, though cyclone 04A was first identified at 18Z 28th September.

Choice of forecast start time

The system was fairly slow moving. The observations suggested that a run from 00Z 26th September 1998 would capture the early stages of Monsoon flooding.

AP1 Results

There is a gradual deepening of the broad cyclone over the Bay of Bengal. Again, there is a strong diurnal cycle of convection over land. Perhaps the most interesting feature is the formation of large, long-lived precipitation 'cells' which propagate - possibly resembling very poorly resolved squall lines. These produce isolated peaks in the rainfall rate (Fig. 31) and accumulation (Fig. 32).

AP4 Results

These are broadly consistent with AP1 (Fig. 33-35) - perhaps the major conclusion is that there is no major deterioration from the proximity of the southern boundary.

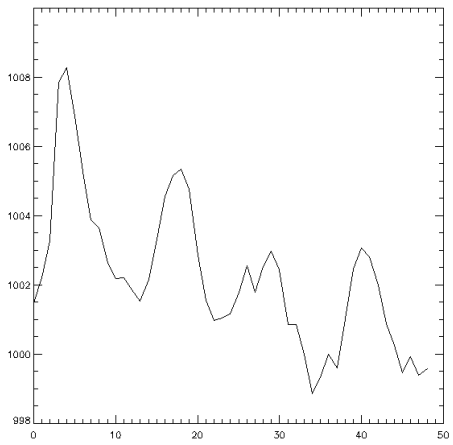


Figure 30. Case 5 AP1 modelled central pressure .

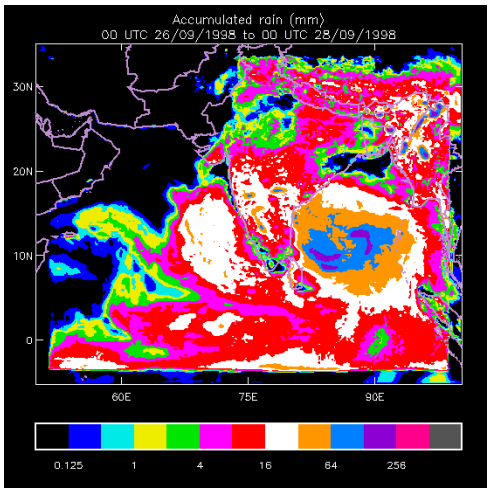
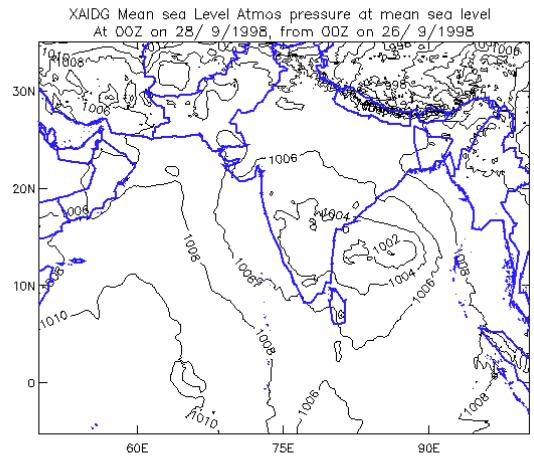
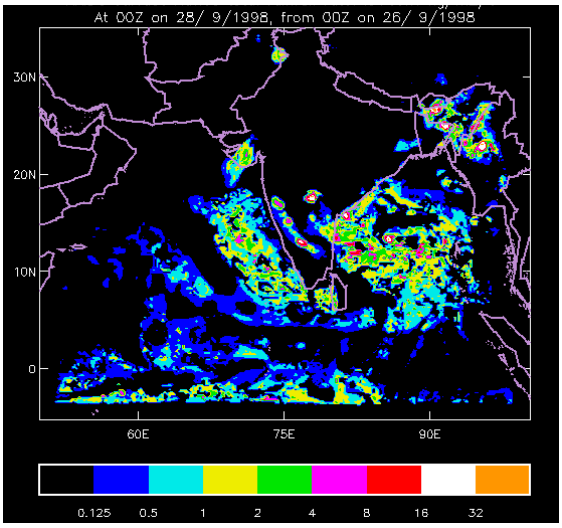


Figure 32 Total rainfall over 48h





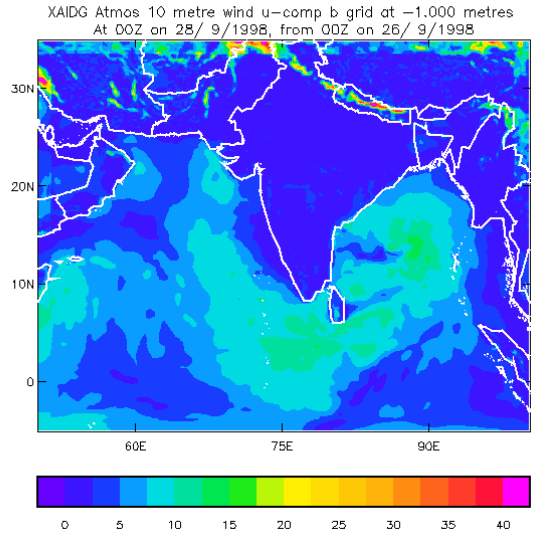


Figure 31. Case 5 AP1 PMSL, surface precipitation rate and 10 m wind speed at T+48.

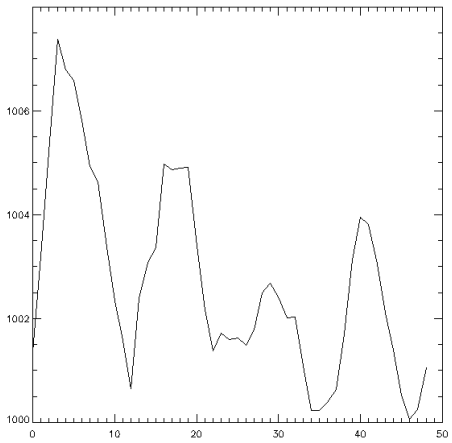


Figure 33. Case 5 AP4 modelled central pressure .

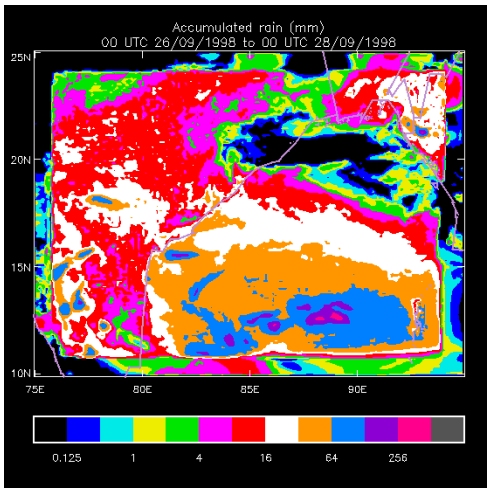
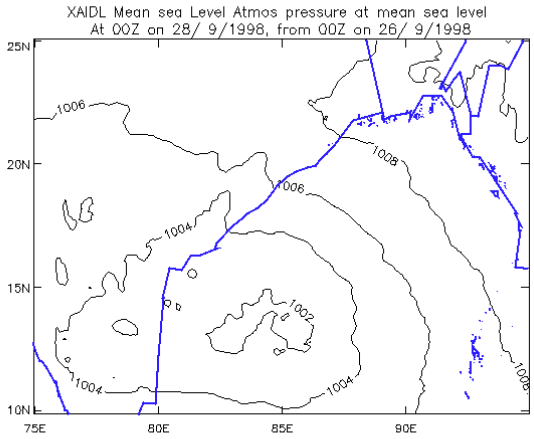
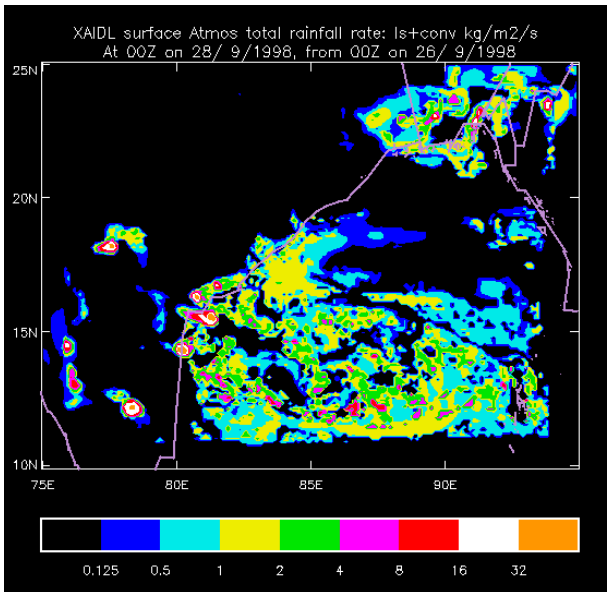


Figure 35. Total rainfall over 48h





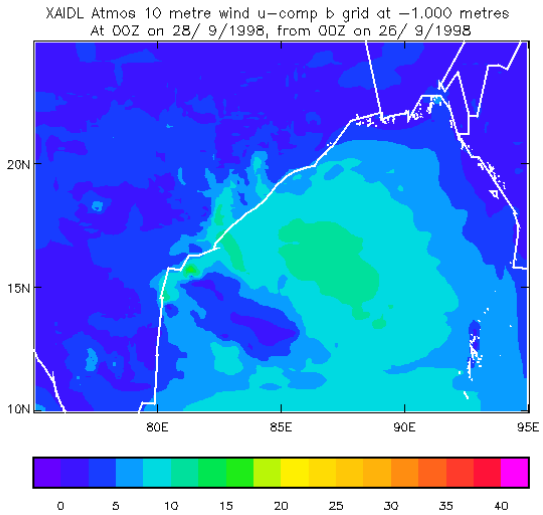


Figure 34. Case 5 AP4 PMSL, surface precipitation rate and 10 m wind speed at T+48.

6 Comparison between Met Office runs and PUM results.

The local implementers of the PUM have run all five cases and provided pictorial output for a number of variables:

1. Pressure at Mean Sea Level.
2. U component of 10 m wind.
3. V component of 10 m wind.
4. Total precipitation accumulation.
5. Convective precipitation accumulation.

These have been compared with equivalent from the T3E runs. Results are shown below for domain AP1 at T+43 (or accumulation from T+42 to T+43) for 1, 2 and 4, for the sake of space. Equivalent contours have been used but no attempt has been made to set up equivalent colour schemes. Precipitation is only shown over a sub region. No attempt has been made to compare results quantitatively; this is, in part, because of the practicality of transferring data between the systems, but also because it is regarded as unnecessary given the obvious closeness of the runs and the anticipated differences between the codes.

6.1 Case 1

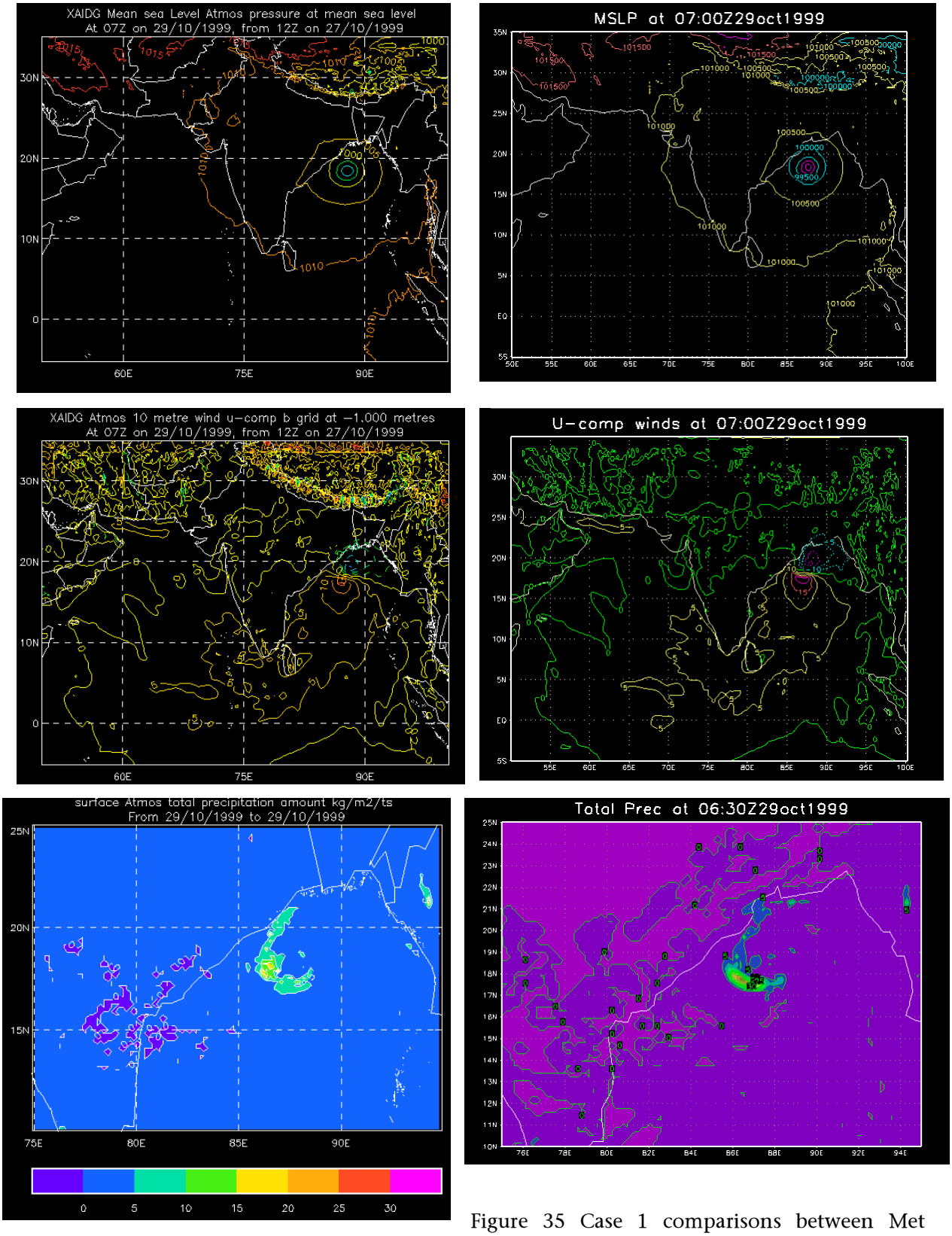


Figure 35 Case 1 comparisons between Met Office (left) and GOAP PUM (right)

6.2 Case 2

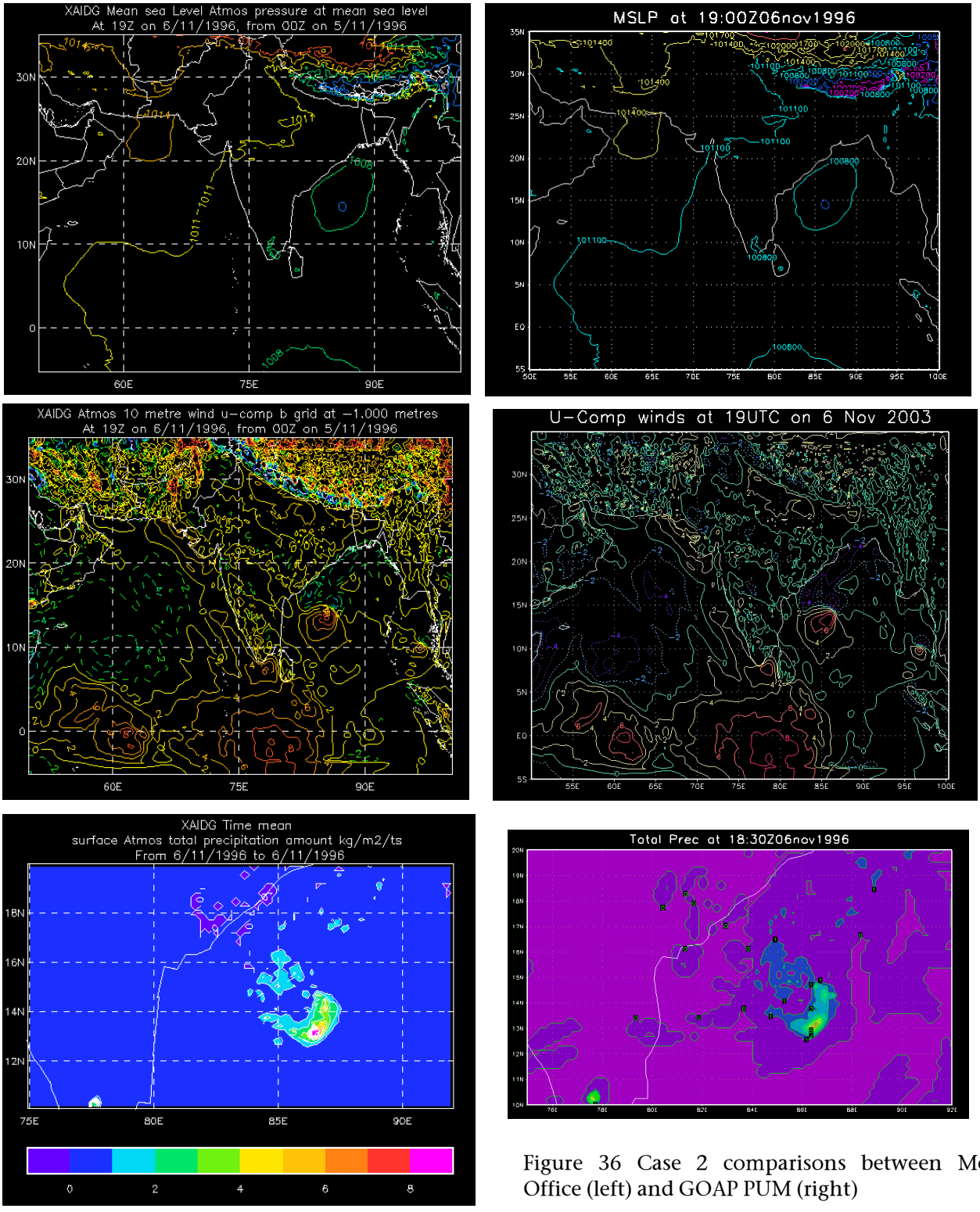


Figure 36 Case 2 comparisons between Met Office (left) and GOAP PUM (right)

6.3 Case 3

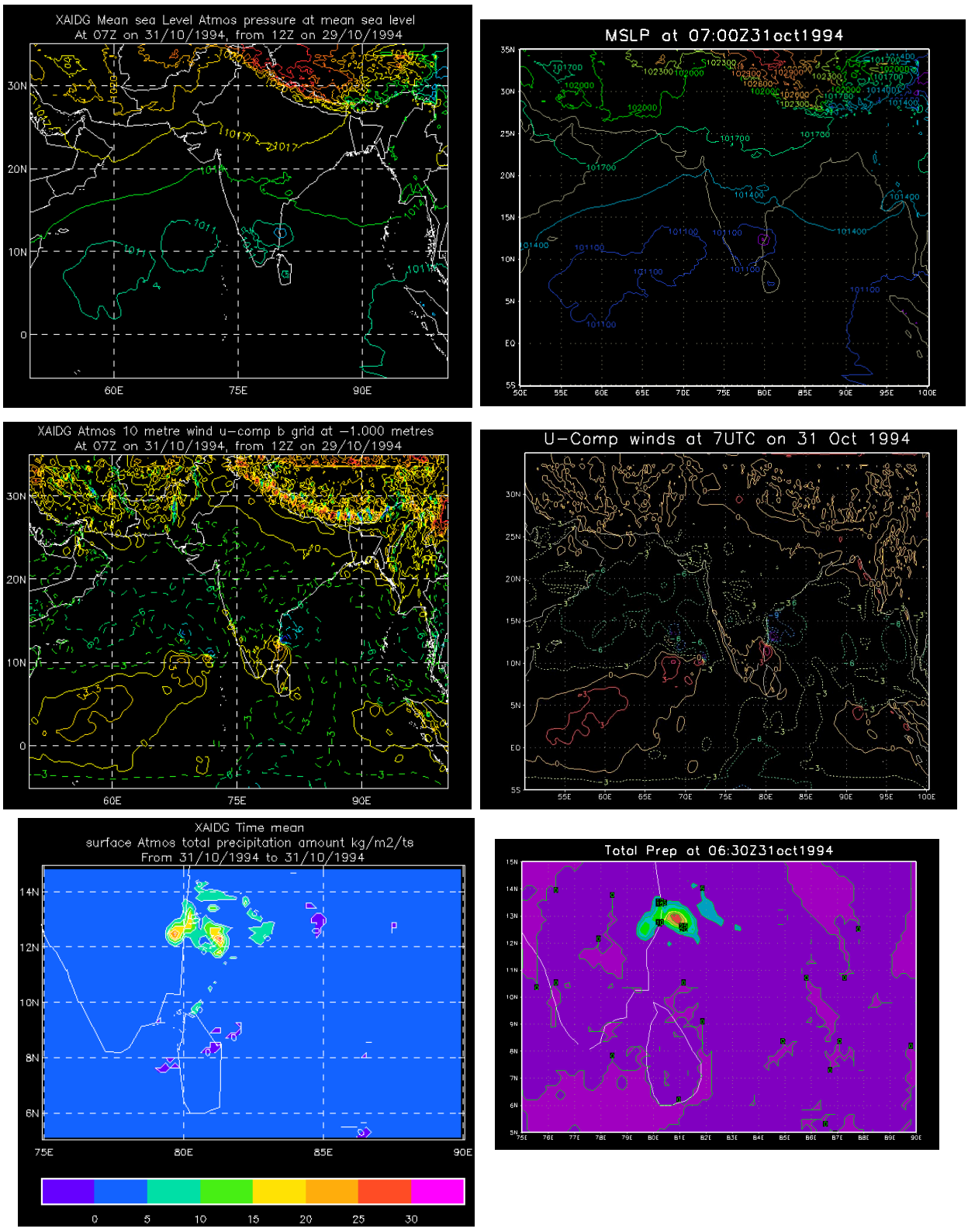


Figure 37 Case 3 comparisons between Met Office (left) and GOAP PUM (right)

6.4 Case 4

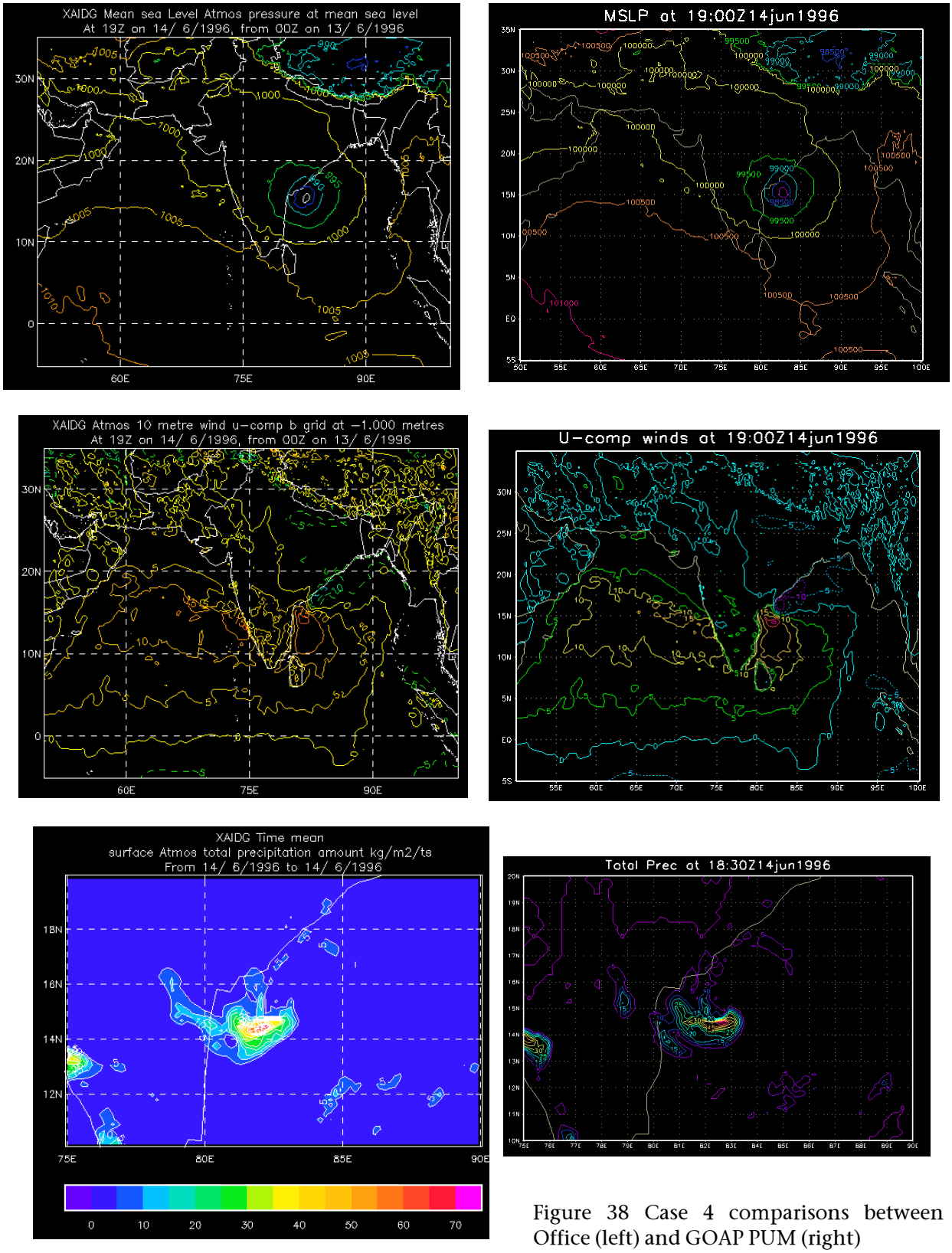
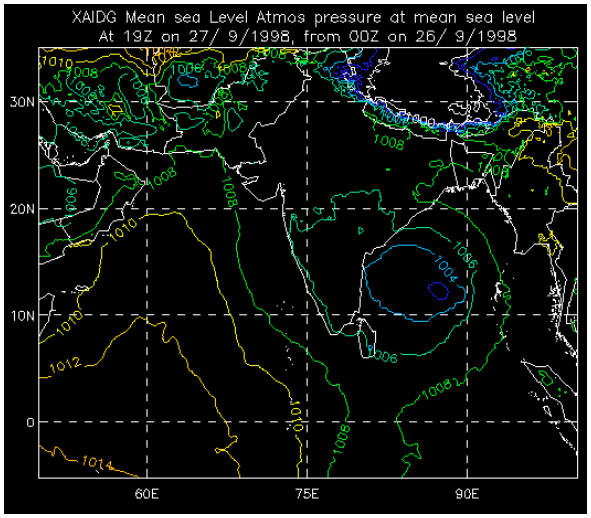
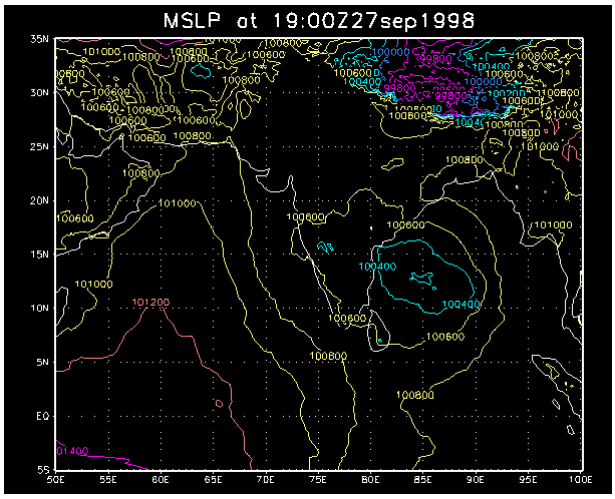
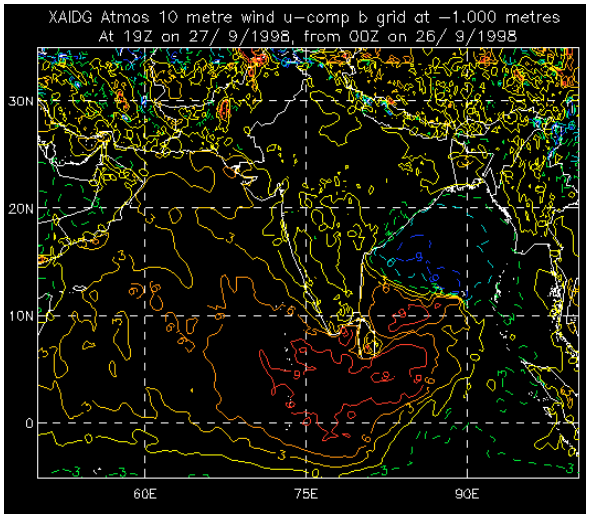


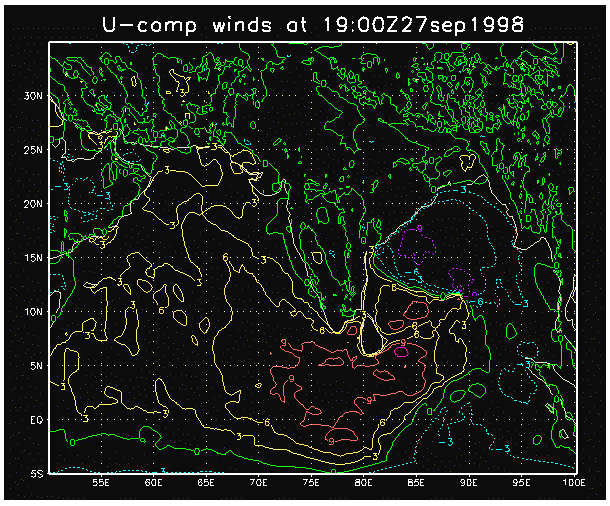
Figure 38 Case 4 comparisons between Met Office (left) and GOAP PUM (right)

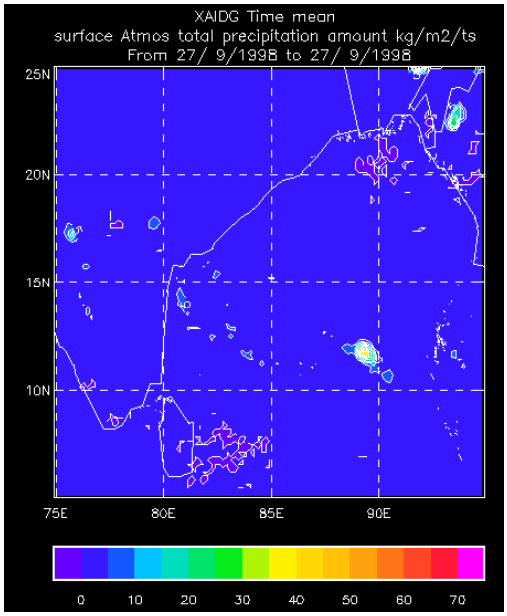
6.5 Case 5











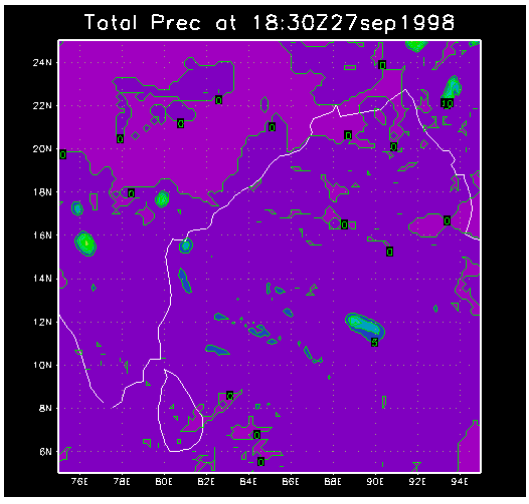


Figure 39 Case 5 comparisons between Met Office (left) and GOAP PUM (right)

6.6 Comments on comparisons

It is clear from the comparisons that the PUM runs are very similar to the Met Office runs in almost all respects. PMSL is almost identical in all cases, and 10 m wind is similarly close over almost all the domain. The exception, consistent from case to case, is the 10 m wind on the ridge of the Himalayas and, to a lesser extent, in the boundary zone. Given the similarity elsewhere and in other variables, this suggests either a difference in the diagnostic code or a difference in the model boundary layer scheme associated with this steep slope. A contender for the latter is the boundary layer scheme, especially the orographic roughness scheme, which has a very high value of peak to trough height for unresolved orography in this region. Since initial dumps are identical, any difference must be in the code or parameters. The latter should be the same, so it is likely that there are differences between the PUM code and the UM in the surface exchange scheme. Without tracing the code in detail, this is highly likely; the surface code was undergoing substantial development, with the introduction of MOSES, during the period that this code was current, so it is highly likely that differences exist. Outside this region, differences are not large enough to cause concern.

Differences in the rainfall field are more noticeable. The model is subject to chaotic error growth. At this resolution, it is noticeable that quasi convective explicit cells develop (i.e. regions of substantial dynamical uplift and large scale rain in convectively unstable areas). These are kept under control by the model, but it is not surprising that small differences, which could be due to compiler differences as well as code differences, grow. The differences are within the variability expected between systems, and are not cause for concern.

Overall, it is clear that the solutions are not identical, and it is very likely that the code implemented at GOAP is not the same as that used on the T3E. This is no surprise and is not a cause for concern. We believe that the solutions are sufficiently close to indicate that the GOAP installation s running correctly.

7 Conclusions and recommendations

The following has been achieved:

1. Successful creation of two domains within UM 4.5 covering the region of interest.
2. Successful creation of UM 4.5 model configurations using these domains.
3. Successful creation of initial and boundary data using the UM 4.5 global model initialised from ECMWF 60 level data for five cases each domain.
4. Successful running of each case. No failures occurred and the results are meteorologically sensible.
5. Successful comparison with the PUM installation.
6. In three out of four cases where cyclones were present in reality, cyclones formed and/or deepened in approximately the right place, and in two cases the track was reasonably well forecast, though generally slow.

The main provisos on the above are a substantial initial transient and subsequent minor semi-diurnal pressure oscillation which are thought to arise from the use of ECMWF data. It is anticipated that, in an operational context, these problems would not arise if data were provided from the operational UM (though some initial adjustment to the introduction of higher resolution data from the Himalayas would probably still occur).

The results highlight the following main conclusions:

- The UM is capable of producing and deepening cyclones.
- The higher resolution model, as expected, deepens faster and further, though neither is capable of producing anything like the depth observed, or the peak windspeeds. This is also expected at the resolutions used.
- In most cases, the forecast quality depended on the analysis of a cyclone in the initial data. The data used contained no bogussing, though the most recent case probably benefited from satellite data.
- Given the performance of the most recent case (Case 1) we anticipate that a good initial state, benefiting from cyclone bogussing, is likely to produce useful forecasts, though whether the track forecast will be superior to the Met Office global model has yet to be demonstrated.

The following recommendations are also made:

- The AP1 domain is probably larger than it need be. The AP4 domain, on the other hand, is probably too small for general use. The benefits to be gained from resolution probably do not outweigh those gained from a larger domain. It is recommended that a strategy is developed which either uses a 0.18 degree grid with a somewhat smaller domain than AP1, or multiple 0.11 degree domains suitable for different circumstances.
- The model is tested using analysis data from more recent events available in the Met Office archive.